EVAUATION OF THE ROD-PINCH DIODE AS A HIGH-RESOLUTION SOURCE FOR FLASHRADIOGRAPHY AT 2 TO 4 MV*

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Abstract

The ASTERIX generator is used to obtain the first evaluation of the rod-pinch electron-beam diode as an intense source of x-rays for high-resolution, pulsed (30- to 40-ns FWHM) radiography at voltages of 2 to 4 MV and currents between 50 and 100 kA. At these levels, the rod pinch exhibits standard diode electrical behavior for 1- and 2-mm diam anodes. The impedance is more sensitive to the ratio of anode-to-cathode radius and to the Marx charge voltage for the 1-mm diam anode. Shots with a 0.5-mm diam anode exhibit rapid impedance collapse. Electrical modeling of a limited number of shots using a physics-based diode model reproduces the measured current. For peak voltages ≥ 4 MV, doses of 20 rad(Si) at 1 m are obtained with a 2-mm diam anode and 16 rad(Si) with a 1-mm diam anode, consistent with the dose/charge scaling with voltage to the 1.3 to 1.6 power. The radiation exhibits a large anisotropy, with 2.7 to 4.5 times more dose off-axis than on-axis. The source diam scales with the anode diam, is independent of voltage, and ranges from 1.8 to 3.1 mm (LANL definition). The largest figure of merit for these non-optimized shots is 4.6 rad(Si)/mm^2 at a peak voltage of 4.3 MV. A composite diode with a large diam carbon-rod anode followed by a smaller-diam tungsten-tip converter shows promise for applications where a small central source feature is desired.

I. INTRODUCTION AND SETUP

The physics of the rod-pinch e-beam diode has been investigated and characterized.[1-3] Also, the application of this diode to high-power, high-resolution, flash radiography at 1 to 2.3 MV has been described.[4,5] In this paper, we present the first evaluation of the rod pinch as a radiography source at peak voltages exceeding 4 MV. For this work, the ASTERIX generator, located at the Centre d' Etudes de Gramat, in Gramat France, is modified to operate in positive polarity.[6] Marx charge voltages, V_{Marx}, between 45 and 75 kV are used. The results in this report are based on a limited set of 20 shots. However, peak voltages exceeding 4 MV were obtained on six shots, allowing a preliminary evaluation of the rod pinch in this new, higher-voltage regime.

The experimental setup is illustrated in Fig. 1. See Ref. [6] for a more detailed description of the ASTERIX generator in positive polarity and of the diode hardware used here, and for a discussion of the electrical measurements. A 3.2-mm diam carbon rod connects the tungsten-rod anode to the anode stalk (center conductor) of ASTERIX.[6] The carbon-tungsten junction is located either 47 or 24 mm from the cathode, depending on the separation between the anode stalk and door.[6] Unless otherwise stated, the tungsten extends 16 mm beyond the cathode with the last 10 mm tapered to a point. Tungsten of 0.5-, 1-, and 2-mm diam are used, and the ratio of the cathode-to-anode radius, r_C/r_A, ranges from 5.5 to 20. A composite diode was also tested. For this diode, the 3.2-mm diam carbon rod extends 18 mm beyond the cathode with the last 8 mm tapered, and transitions to a 1 or 0.5-mm diam, 6-mm long, tapered tungsten tip.

The dose on axis (forward direction) is measured with radiophotoluminescent detectors (RPLs). Independent measurements with CaF_2 thermoluminescent dosimeters on a few shots are consistent with the RPL doses. Doses are measured at 36 cm from the tungsten tip, and inverse-square scaling is used to determine the dose at 1 m. The

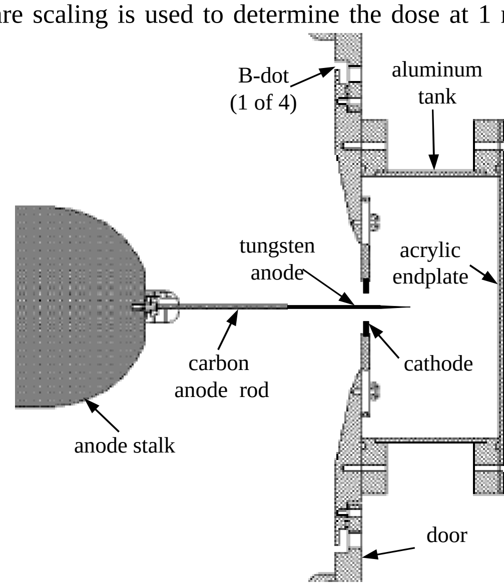

Figure 1. Arrangement of the rod-pinch diode on ASTERIX. Radiation diagnostics include RPLs and TLDs for dose, tungsten rolled-edge and film for source size, and collimated *pin* diodes for isotropy.

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14. ABSTRACT
The ASTERIX generator is used to obtain the first evaluation of the rod-pinch electron-beam diode as an intense source of x-rays for high-resolution, pulsed (30- to 40-ns FWHM) radiography at voltages of 2 to 4 MV and currents between 50 and 100 kA. At these levels, the rod pinch exhibits standard diode electrical behavior for 1- and 2-mm diam anodes. The impedance is more sensitive to the ratio of anode-to-cathode radius and to the Marx charge voltage for the 1-mm diam anode. Shots with a 0.5-mm diam anode exhibit rapid impedance collapse. Electrical modeling of a limited number of shots using a physics-based diode model reproduces the measured current. For peak voltages ³ 4 MV, doses of 20 rad(Si) at 1 m are obtained with a 2-mm diam anode and 16 rad(Si) with a 1-mm diam anode, consistent with the dose/charge scaling with voltage to the 1.3 to 1.6 power. The radiation exhibits a large anisotropy, with 2.7 to 4.5 times more dose off-axis than on-axis. The source diam scales with the anode diam, is independent of voltage, and ranges from 1.8 to 3.1 mm (LANL definition). The largest figure of merit for these non-optimized shots is 4.6 rad(Si)/mm2 at a peak voltage of 4.3 MV. A composite diode with a large diam carbon-rod anode followed by a smaller-diam tungsten-tip converter shows promise for applications where a small central source feature is desired.

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on-axis source diam is determined from analysis of the photographic image of a 1-m radius, tungsten rolled edge (on loan from LANL) located 40 cm from the tungsten tip.[4] Source magnifications (G) of 3 and 4 are used. Three, lead-collimated *pin* diode detectors filtered with 6-mm-thick lead are used to record radiation time histories at 10° (nearly the forward direction), 45°, and 80° to the anode axis. For the conditions of this experiment, measurements and calculations confirm that the time-integrated *pin* signals, properly normalized, scale linearly with the dose.

II. ELECTRICAL BEHAVIOR

The electrical data for a shot with a 1-mm diam anode are displayed in Fig. 2. The diode voltage, V_{load}, total diode current (electron + ion), I_{load}, and impedance, Z_{load} (= V_{load}/I_{load}), are plotted as a function of time. Also shown is the *pin* signal at 10°. We define a "characteristic" electrical parameter as the 8-ns average of that parameter about the maximum of this radiation signal. So defined, the characteristic load voltage, current and impedance for this shot are 3.6 MV, 95 kA, and 37 Ω, respectively. The peak voltage is 4.3 MV. The average time rate of change of the load impedance, $\langle dZ_{load}/dt\rangle$, over the full width at half maximum (FWHM) of the radiation pulse is -0.5 Ω/ns. For all the ASTERIX data, we define the impedance as "acceptable" when $|\langle dZ_{load}/dt\rangle| \leq 1$ Ω/ns. This usually corresponds to a factor of two or less decrease in Z_{load} during the radiation FWHM.

For 2-mm diam anodes, acceptable impedance is observed for all the conditions tested: r_C/r_A = 5.5 and 11 at V_{Marx} = 50 kV, and r_C/r_A = 7.5 and 11 at V_{Marx} = 75 kV. Acceptable impedance is observed with 1-mm diam anodes for r_C/r_A = 8.5 and 20 at V_{Marx} = 50 kV, for r_C/r_A = 11 at V_{Marx} = 55 and 60 kV, and for r_C/r_A = 16 at V_{Marx} = 75 kV. The impedance with 1-mm diam anodes is more sensitive to r_C/r_A and to V_{Marx} than with 2-mm-diam anodes. For example, a 1-mm anode with r_C/r_A = 14 at V_{Marx} = 75 has rapid impedance decay (-1.84 Ω/ns), but exhibits acceptable impedance decay (-0.5 Ω/ns) with r_C/r_A = 16 (Fig. 2). We conjecture that this sensitivity is a result of increased energy deposition leading to enhanced electrode plasma expansion, which, because of the cylindrical nature of the rod pinch, results in a more rapid impedance decay with smaller diam anodes.[2,4] This conjecture is supported by the fact that rapid impedance collapse is observed on the two shots with 0.5-mm diam anodes (r_C/r_A = 16 at V_{Marx} = 45 kV and r_C/r_A = 11 at V_{Marx} = 50 kV).

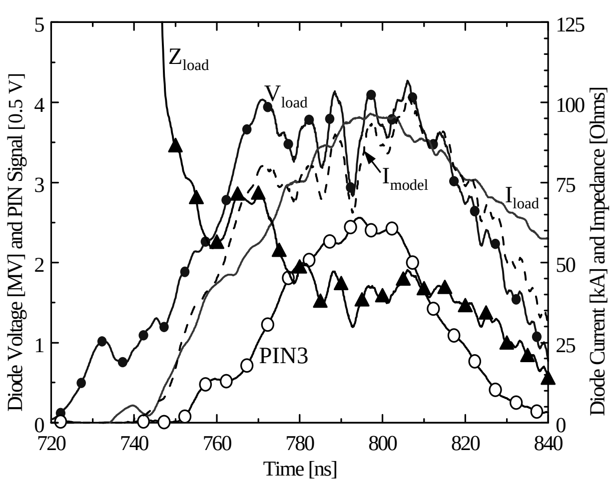

Figure 2. Electrical waveforms (Vl_{oad}, I_{load}, Z_{load}) for a well-behaved 4-MV shot. The radiation signal at 10° is PIN3. The model current, I_{model}, is compared with I_{load}.

The current, I_{model}, calculated using V_{load} and a physics based rod-pinch model[1,2] is plotted in Fig. 2 as a dashed line. In this model, the current transitions from the Langmuir-Blodgett (L-B) current to the critical current as the voltage increases during the pulse. Physically reasonable values (not very different from those found in Ref. [2]) are used for the adjustable parameters. The initial value for the multiplication factor used in the critical current formula is $\alpha_o = 2.6$.[1,2] I_{model} is in reasonable agreement with I_{load}. The transition from L-B to critical current occurs near 755 ns. The model also predicts that the ion current is about 20% of the total current.

III. DOSE SCALING AND ISOTROPY

The dose/charge (dose/Q) in the forward direction is plotted as a function of the characteristic load voltage in Fig. 3 for shots with acceptable impedance. Q is determined by integrating I_{load} until the time after peak

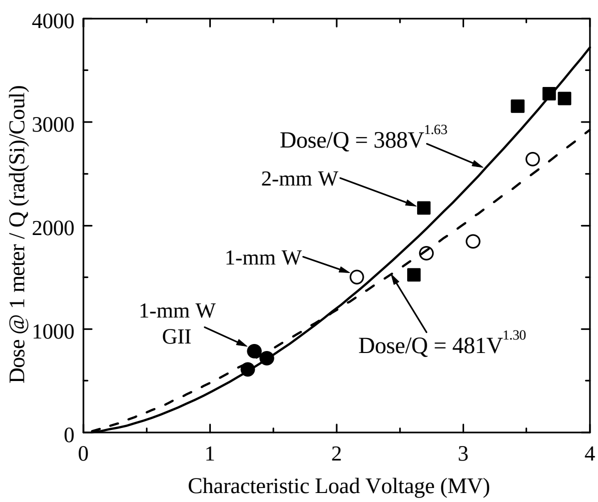

Figure 3. Scaling of the measured dose, normalized to charge, with the characteristic voltage. The squares and open circles are ASTERIX measurements for 2-mm and 1-mm diam anodes, respectively. The filled circles are Gamble II measurements.

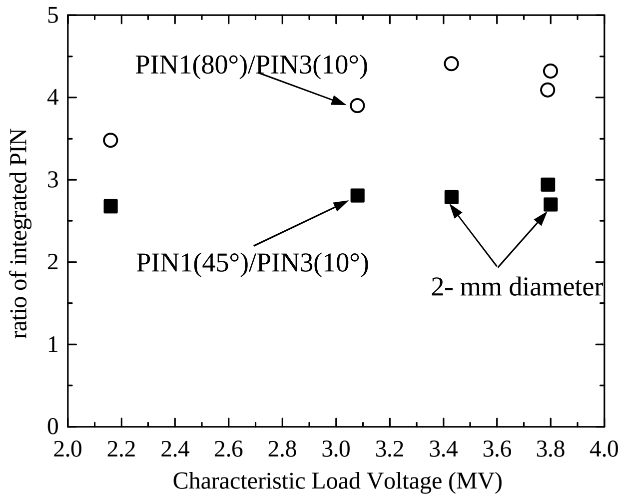

Figure 4. Radiation anisotropy determined with the *pin* diodes.

radiation when the signal has decreased to 5% of its maximum value. Results from Gamble II for 1-mm diam anode geometry identical to ASTERIX are included in Fig. 3. Doses as large as 20 rad(Si) for a 2-mm diam anode and 16 rad(Si) for a 1-mm diam anode are achieved at the highest voltages, compared with 2.5 rad(Si) for the Gamble-II, lowest-voltage data. Power-law fits to the 2-mm diam (ASTERIX only) and 1-mm diam (ASTERIX + Gamble II) data suggest that the dose/Q scales with V_{load} to the 1.3 to 1.6 power. At higher voltages, the 2-mm diam anode is a more efficient radiation converter than the 1-mm diam anode. The continuous-slowing-down-approximation (CSDA) range for electrons with energy near 2.5 MeV in tungsten is about 1 mm, suggesting that the smaller dose/Q for the 1-mm diam anode may be a result of the rod becoming sub-range to higher energy electrons. However, this conjecture does not take into account the taper.

The integrals of the *pin* diode signals are used to determine the radiation isotropy. No significant differences in the shapes of the time-resolved signals at 10°, 45°, and 80° are observed in this experiment. Ratios of integrated signals for 45°/10° and 80°/10° are presented in Fig. 4 for shots with 1-mm or 2-mm diam anodes that have acceptable impedance. Over the range of voltages sampled, the 45°/10° ratio is about 2.7, independent of voltage. The 80°/10° ratio increases with voltage from 3.5to 4.5, suggesting the dose at 80° scales with a higher power of voltage than observed in the forward direction. Some of the large anisotropy is a result of different filtering of the radiation by the vacuum chamber walls on-axis compared with off-axis.[6] PIC simulations combined with electron/photon transport calculations are being used to evaluate this effect. The large anisotropy should be eliminated to optimize on-axis radiography. On the other hand, to take advantage of this off-axis emission the off-axis source size should be reduced. One option is to use a hollow (thin range) low-atomic-number (low-Z) anode rod with a 1-mm diam, high-Z ball at the tip.[7]

IV. SOURCE DIAMETER

The source diam is deduced from the film image of the rolled edge, which gives the edge spread function (ESF). The derivative of the ESF is the line spread function (LSF). One measure of the source diam is the average FWHM, <FWHM>, of the LSF obtained from fits to the LSF for uniform-circular disk, Gaussian, and Bennett radial source distributions. The central feature of the radial distribution dominates this measure. Another measure is the 50% point of the modulation transfer function (Fourier transform of the LSF). This LANL measure (used extensively at Los Alamos National Laboratory) incorporates the wings of the source distribution and results in a larger source diam. Results from both measures are plotted as a function of anode diam in Fig. 5 for shots with acceptable impedance behavior. The solid lines are linear fits to the data, while the dashed line is an extrapolation (see Sec. V). The source diam increases with anode diam, but somewhat less than 1:1, similar to the behavior observed for rod-pinch loads on Gamble II.[4] For fixed anode diam, the source diam is constant (within experimental uncertainty). The <FWHM> is generally less than the anode diam. Further analysis shows that the source diams are independent of characteristic voltage from 2.1 to 3.8 MV. For shot 6403 (Fig. 2), the figure of merit (dose @ 1 m/[LANL source diam]^2) is 4.6 rad(Si)/mm^2.

V. COMPOSITE DIODE

The composite diode is designed to avoid the sensitivity of impedance decay to r_C/r_A associated with 1- and 0.5-mm diam anodes by using a larger diam, low-Z anode. Rapid and efficient e-beam propagation from the anode to a smaller diam, higher-Z tip is relied on to maintain a

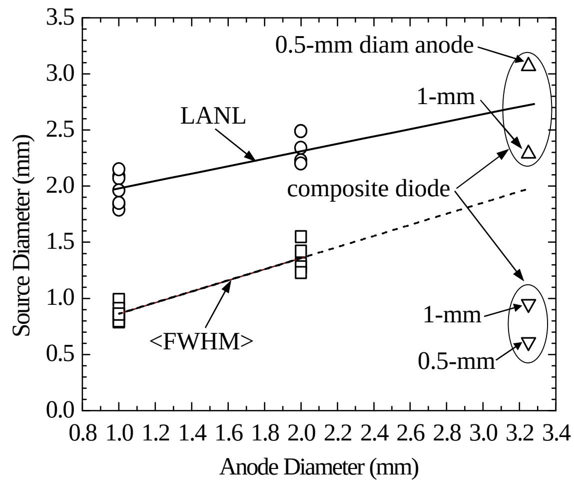

Figure 5. Source diams determined from the <FWHM> measure (squares) and from the LANL measure (circles). The solid lines are linear fits to the data. The dotted line is an extrapolation. Composite rod results for 1- and 0.5-mm diam tips are also shown (triangles).

small source diam. With larger r_A, the specific energy deposition on the anode surface and the fractional change in r_A from plasma expansion are both reduced. The electrical behavior of the composite diode with a 0.5-mm diam tip is similar to shot 6403 (Fig. 2). The on-axis dose at 1 m for this composite-diode shot is 9 rad(Si), 5.4 times larger than the average dose measured for the standard-diode, 0.5-mm diam anode, rapid-impedance-collapse shots. However, this dose is 1.8 times smaller than the dose measured on shot 6403, suggesting a non-optimum diode geometry and/or reduced efficiency with smaller diam converters. Source diams for two composite-diode shots are shown in Fig. 5. The LANL source diams are somewhat less than the carbon anode diams. The <FWHM> do not follow the standard-diode extrapolation and are about equal to the diam of the respective tungsten tip, i.e., 3.4 to 5.3 times smaller than the 3.2-mm diam carbon anode. This analysis suggests that a small diam central feature is preserved, while significant radiation is present in the wings of the distribution, presumably from the carbon anode. More work is required to minimize the radiation from the large diam anode (e.g., use a hollow, sub-range anode) and to maximize the dose (e.g., optimize the extension beyond the cathode).

VI. SUMMARY AND CONCLUSIONS

The ASTERIX generator at CEG is used to evaluate the rod-pinch diode as an intense source of x-rays for high-resolution, pulsed radiography at voltages of 2 to 4 MV, currents between 50 and 100 kA, and r_C/r_A from 5.5 to 20. Tapered tungsten rods of 0.5-, 1-, and 2-mm diam served as the anode. With 2-mm diam anodes, acceptable impedance behavior is observed for all the conditions tested. For 1-mm diam anodes, the impedance is more sensitive to r_C/r_A and V_{Marx}, possibly due to increased specific energy deposition and to proportionally larger anode expansion. For a 1-mm diam anode, acceptable impedance behavior is observed for $r_C/r_A = 16$ at $V_{Marx} = 75$ kV. Rapid impedance collapse is observed for all 0.5-mm diam anodes. Analysis of a limited number of shots with a physics-based diode model reproduces the measured currents, but more work is needed in this area. For the highest voltage shots, measured on-axis doses at 1 m are 20 rad(Si) for 2-mm diam rods and 16 rad(Si) for 1-mm diam anodes, consistent with dose/Q scaling as voltage to the 1.3 to 1.6 power. The radiated emission is anisotropic with a 45°/10° ratio of 2.7 and an 80°/10° ratio of 3.5 to 4.5. The anisotropy at 45° appears to be independent of voltage, while the anisotropy at 80° increases with voltage. More data and analysis are required to quantify and understand the voltage scaling and dose anisotropy. The on-axis source diam scales with the rod diam and is independent of voltage. The LANL source diam varies from 1.8 to 3.1 mm and the <FWHM> of the LSF ranges from 0.6 to 1.6 mm. The largest figure of merit is 4.6 rad (Si)/mm^2, obtained with a 1-mm diam anode at a peak voltage of 4.3 MV. The composite diode operates with acceptable impedance and produces a dose 5.4 times larger than obtained from a standard diode with a 0.5-mm diam anode, while preserving the small central feature associated with the 0.5-mm diam tip. The results of this investigation indicate that the rod-pinch can be a very useful source for high-resolution, pulsed radiography at voltages up to 4 MV.

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